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Procedia Engineering 125 (2015) 732 – 738

Procedia Engineering

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The 5th International Conference of Euro Asia Civil Engineering Forum (EACEF-5)

Enhancing the performance of porous concrete by utilizing the pumice aggregate

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Abstract

High porosity, low modulus of elasticity, and adequate strength are the main requirements of the concrete structures as an impact energy absorber. The development of porous concrete mainly focuses on increasing the porosity rather than the strength due to many advantages can be gained when having higher porosity. Consideration to the environmental problem has been a concern recently, therefore utilization of a waste material as construction materials has been spreading widely. Volcanic pumice as one of waste materials having a high porosity can possibly be utilized as an aggregate replacement material on porous concrete to improve its porosity without much reducing the strength. The purpose of this research is to evaluate the effect of varying proportion of volcanic pumice as an aggregate replacement (VP/A) and proportion of aggregate to cement (A/C) with a constant water to cement ratio (WCR) to the mechanical properties of volcanic pumice porous concrete, and to those porous concrete with normal aggregate as a control. The result shows that by using volcanic pumice the porosity increases and the modulus of elasticity decreases, even though slightly decreasing in strength is also found. However, it showed a possibility of volcanic pumice porous concrete as impact energy absorber structures. This research is a preliminary study which is expected to be developed for future research related to the dynamic and impact test. In addition, ACI 318-08 developed equation ($E_c = 0.043W^{1.5}f'_c{}^{0.5}$) can be used to rapidly estimate the modulus of elasticity of porous concrete, where it is necessary, due to experimental difficulties to measure it.

Peer-review under responsibility of organizing committee of The 5th International Conference of Euro Asia Civil Engineering Forum (EACEF-5)

Keywords: porous concrete; mechanical properties; volcanic pumice; aggregate replacement; aggregate-cement ratio

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Peer-review under responsibility of organizing committee of The 5th International Conference of Euro Asia Civil Engineering Forum (EACEF-5)
doi:10.1016/j.proeng.2015.11.116

1. Introduction

Porous concrete as one of concrete family have the same compositions as conventional concrete consisting of cement, water, and aggregate, with the exceptions that the fine aggregate typically is reduced or even omitted entirely, and the size distribution of coarse aggregate is kept narrow grading. This provides not only the useful hardened properties, but also results in a mix requiring different considerations in mixing design, mixing procedures, placing, compaction, and curing [1].

Recently the raising for consideration to the environment and sustainable management are noticeable and promote on utilizing porous concrete. This concrete can be a successful means in addressing a number of environmental issues and supporting sustainable development. Despite of having a lower strength, the porous concrete with a higher porosity is useful for many applications, such as permeable pavement [2], purifying water [3,4], heat reducer [5,6], and sound absorber [7]. Porous concrete has been widely applied for rain stormwater and has been successfully used for filtering the water and reducing pollutant loads that enter into the streams, ponds, and rivers [8]. The range of porosity that was generally expected for porous concrete for pavement and other applications was about 15% to 25% [9].

In the last decade, the investigation on the civil infrastructure safety and its failure mode that being exposed to various severe loadings during their serviceability condition have attracted more attention. Structural element might initiate failure when subjected to severe loading, such as impact loading as the one of the important loading types. On the other hand, structural element has to remain sustainable due to the impact loading. Check dam structures, highway columns, concrete road barrier, subway wall, and rock fall protection structures are some structures that commonly subjected to impact loads. Many methods can be used to reduce the impact energy, one of them is by applying impact energy absorber layer on these structures. Porous concrete having a lot of voids and a lower elastic moduli are expected can be used as an impact energy absorber due to the self-structure destruction when subjected to impact load, and potentially be able to demonstrate the cushioning characteristics. To date, there are no reports on the data related to the effect of volcanic pumice as aggregate on the porous concrete performance, particularly on the impact energy absorption. Therefore, here we conduct the investigation on the volcanic pumice porous concrete. The aim of this research is to present the experimental results of a study undertaken in the following areas: 1) the void content of volcanic pumice porous concrete and the effect of the volcanic pumice proportion on it; 2) the influence of mixture proportion and volcanic pumice proportion on the compressive and tensile strength (flexural strength) of concrete.

2. Experimental Program

2.1. Materials

Materials used for making porous concrete in this research were ordinary Portland cement, normal coarse aggregate, volcanic pumice, water, and plasticizer. Ordinary Portland cement with specific gravity 3.15 and blaine of 3,280 cm^2/g was used to make several mixes. The superplasticizer used was a combination of BASF Rheobuild SP8N and BASF Micro-Air 785 with composition 90% and 10% respectively, and an average specific gravity of 1.045. Various sizes crushed limestone coarse aggregate 5-20 mm with the fineness modulus 6.85 was used and also volcanic pumice with the same size for partially aggregate replacement. The material data of normal aggregate were specific gravity 2.670, water absorption 1.14 %, and saturated surface-dry (SSD) bulk density 1,682 kg/cm^3. While the material data of volcanic pumice were specific gravity 1.587, water absorption 53.25 %, and saturated surface-dry (SSD) bulk density 822 kg/cm^3. Hardness aggregate evaluated by Los Angeles abrasion test was 38.4% for volcanic pumice.

2.2. Mix proportions

The absolute volume of all ingredients in the mixtures was kept constant for all samples with the total of porosity theoretically also constant. The proportioning of porous concrete mixtures is summarized in Table 1.

Table 1. Mixture proportions.

Mixture	Aggregate size (mm)	A/C	VP/A (%)	WCR	Cement (C) kg/m³	Volcanic Pumice (VP) kg/m³	Normal aggregate (A) kg/m³	Water liter/m³	Plasticizer kg/m³
4VP0	5-20	4	0	0.25	435	-	1478	104.6	4.35
4VP50	5-20	4	50	0.25	435	439	739	104.6	4.35
4VP100	5-20	4	100	0.25	435	878	-	104.6	4.35
8VP0	5-20	8	0	0.25	258	-	1746	62.0	2.58
8VP50	5-20	8	50	0.25	258	519	873	62.0	2.58
8VP100	5-20	8	100	0.25	258	1038	-	62.0	2.58

Note: Mixture 4VP50 = 4 proportion of aggregate to cement (A/C = 4), and 50% of volcanic pumice as aggregate replacement.

2.3. Testing procedures

After casting, the weight of specimen with mold was measured and then cured to a moist room at 20°C and 90 percent relative humidity for 24 hours. After being demolded the specimen was transferred to a water-curing room at 20°C until 28 days for testing.

The void content of porous concrete (A_t) was measured according to the test method proposed by the ASTM C1754/C1754M-12 [10] that is based on volume method. The weight of the specimen after drying in the oven was (W_2). After oven drying the specimen was submerged in water at 20°C for 30 minutes and tapped 10 times with a mallet, subsequently the specimen was weighted to measure the submerged weight (W_1). While V is the total volume of specimens and ρ_w is the density of water.

$$A_t = \left(1 - \left(\frac{W_2 - W_1}{\rho_w \times V}\right)\right) \times 100\% \tag{1}$$

The measurement of compressive strength of porous concrete was conducted after 28 days in accordance with JIS A 1108 [11]. A stiff machine with a 3000 kN capacity was used to perform this test on 100mm x 200mm cylinder specimens. The displacement of each specimen was measured using a compressometer during the compressive strength test for determining the modulus of elasticity. To reduce the variation for modulus elasticity due to the honeycomb structure of porous concrete, small local capping by cement paste were laid in all contact points between compressometer and specimen. The flexural strength test was conducted on 100x100x400 mm beam specimens in accordance with JIS A 1106 [12].

3. Result and discussion

Table 2 summarizes the properties and strength test results of porous concrete at the ages of 28 days. The data shown is the average of a number of data with the identical mixture proportion.

Table 2. Summary of laboratory testing results

Mixture	Density (kg/m3)	Void Content (%)	Compressive Strength (MPa)	Modulus of Elasticity (MPa)	Flexural Strength (MPa)	Deflection Maximum of Flexural test (mm)
4VP0	2039.12	24.33	22.50	21680.87	2.67	3.57
4VP50	1852.03	25.12	12.36	13389.52	2.33	2.80
4VP100	1560.89	30.02	9.50	6305.77	1.78	2.47
8VP0	1858.71	34.99	14.38	16269.38	1.46	2.71
8VP50	1623.05	37.58	7.39	7371.93	1.70	2.59
8VP100	1189.68	36.62	2.76	2594.70	1.32	2.03

3.1. Density and void content

The relationship between density and void content of volcanic pumice porous concrete can be seen in Fig. 1. The graphic of another researcher's results [13] was also plotted for comparison. The graph shows that the porous concrete density of this research is lower than that of Lian's results. It indicates that volcanic pumice effectively decrease the porous concrete density. Thus, it will be applicable when low density of structures is needed, for example on energy absorbing structures that of the structures should have a high energy-absorption capacity per unit weight [14].

3.2. Compressive strength and modulus elasticity

Fig. 2(a) depicts a relationship between compressive strength of volcanic pumice porous concrete that tested after 28 days of water curing and modulus of elasticity. The graphics of another researcher's results [15], ACI standard for lightweight concrete (ACI 213R-03) [16], and ACI standard for structural concrete (ACI 318-08) [17] are also plotted for comparison. The ACI's lightweight concrete standard is used for comparison due to the porous concrete is also categorized as lightweight concrete [18]. It can be seen that the increment in compressive strength is proportional to that in the modulus of elasticity. One of the ACI diagrams that used here is the ACI for lightweight concrete with a blend of lightweight and normal weight aggregate (ACI 213R-03), as the research also used combination the normal aggregate and volcanic pumice (lightweight aggregate). The graph shows that the modulus of elasticity of porous concrete that obtained is significantly lower than ACI standard for lightweight concrete. Lowering of elastic modulus of porous concrete indicates that the strain under compression loading in porous concrete increases faster than normal concrete and lightweight concrete. The strain development of porous concrete may be accelerated due to the omitting of fine aggregate on porous concrete. Hence, the concrete creeps rapidly when the bonding connection between aggregates by cement paste have reached a maximum stress. Based on these results, it can be assumed that the porous concrete has a high deformability, so it is potential to be utilized as impact energy absorber.

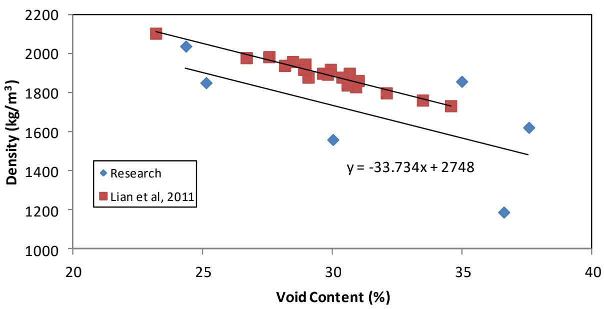
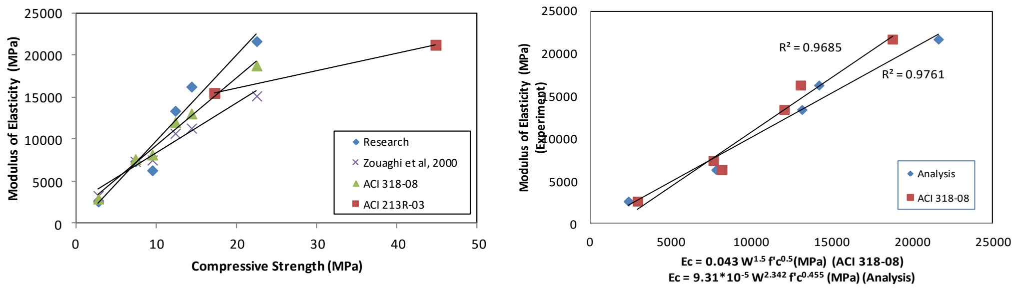


Fig. 1. Relationship between density and void content

Comparison between the results and other research and ACI 318-08 is also displayed in Fig. 2(a). Another researcher showed a lower modulus of elasticity result than this research which is inferred due to a higher aggregate to cement proportion and a higher water to cement ratio in their composition [15]. However, all of three lines (the results, Zouaghi's, and ACI 318-08's) showed linearities and closely coincidence. Fig. 2(b) shows that the modulus of elasticity of the research can be formulated as a function of unit weight (W) and compressive strength (f'_c) of porous concrete. Regression analysis generated to the following equation: $E_c = 9.31 * 10^{-5} * W^{2.342} * f'_c{}^{0.455}$ with an R^2 value of 0.9761. In addition, the experimental values are relatively close to that of calculation using ACI 318-08 developed equation ($E_c = 0.043 * W^{1.5} * f'_c{}^{0.5}$) with a regression factor R^2 value was found to be 0.9685 (Fig. 2(b)). Therefore, ACI 318-08 developed equation can be used to rapidly estimate the modulus of elasticity of porous concrete, where it is necessary, due to experimental difficulties to measure it.



(a) (b)

Fig. 2. (a) Relationship between modulus of elasticity and compressive strength; (b) Comparison of modulus of elasticity of the research and ACI 318-08 equation.

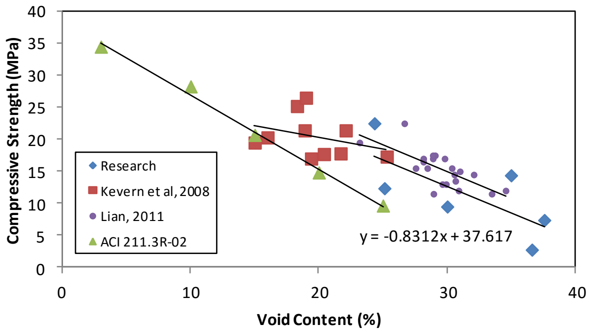
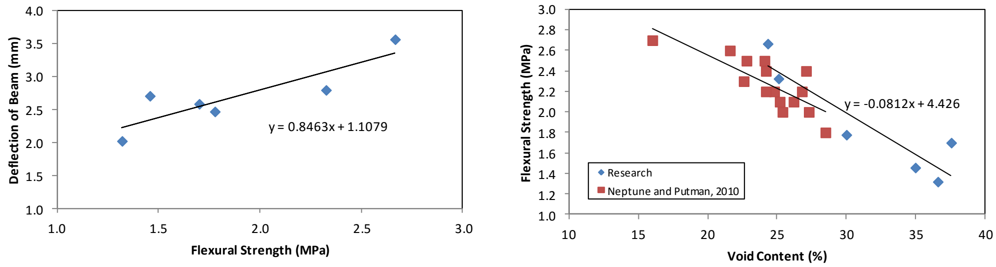


Fig. 3. Relationship between compressive strength and void content.

Fig. 3 shows the correlation between the void content and the compressive strength of the porous concrete. The ACI 211.3R-02 standard [19] and Kevern et al [20], and Lian [13] also included in this plot as a comparison. The results show the linear relationship between compressive strength and void content. The compressive strength significantly decreases as the void content increases. The porous concrete with a void content over 32% have the compressive strength below 10 MPa, which is in agreement with the result reported by [21] where the void content was also found to be over 30%. The line graph found in this research is parallel to the Lian's graph and the compressive strength was slightly lower than Lian's results, since their research used a smaller aggregate grading (4.75-13.2mm). The tendency of the results is also in parallel with the ACI's graph, even though the void content of this research is higher than ACI standard. On the other hand, there is a slight discrepancy between both graphs, the results and ACI, and Kevern's graph. On account of Kevern's graph shows a lower decline, it indicates that the effect of void content to the strength is smaller than the research and others.

3.3. Flexural strength and deflection of beam

The Flexural strength test in this research not only evaluate the strength but also measure the deflection of concrete beams. Porous concrete is a brittle material, even may be more brittle than normal concrete as avoiding the fine aggregate in the mixes. The research tries to find a simple correlation between load and deflection in porous concrete beams. Fig. 4(a) shows the deflection of beam as a function of flexural strength. Porous concrete is a brittle material, therefore the deflection maximum was found on the maximum load and failure of the beam was carried out instantly after the maximum elastic stress was reached without plastic forewarning. The Fig. 4(a) also indicates that the increasing deflection will be found on the point of flexural strength grow in a linear relationship.



(a) (b)

Fig. 4. (a) Relationship between flexural strength and deflection; (b) Relationship between void content and flexural strength.

The effect of void content to the flexural strength are demonstrated in the Fig. 4(b). From the figure, it can be seen that flexural strength decreases rather linearly as the void content increases, especially when the void content is between 25% to 35%. The relationship is given by: MR = -0.0812V + 4.426 where, MR = modulus of rupture (flexural strength in MPa); and V = void content in percent. These results are similar to the result of Neptune et al [22] but with a slightly higher flexural strength.

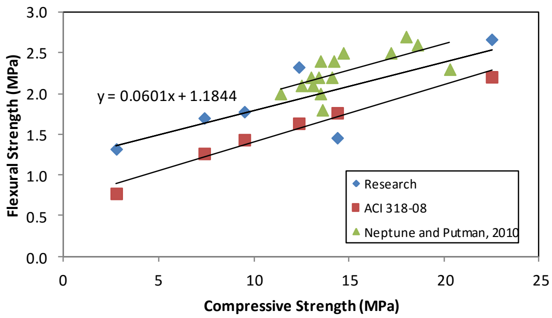


Fig. 5. Relationship between compressive and flexural strength.

Fig. 5 shows a good agreement between compressive and flexural strength of volcanic pumice porous concrete tested after 28 days from this study. The correlation between flexural and compressive strength of concrete is important in the estimation of the flexural strength of concrete mixture, especially in cases in which only compressive strengths are available. The expected trend of flexural strength increasing as compressive strength increased was demonstrated in the results. The results indicated a correlation between the compressive and flexural strengths of porous concrete mixtures included in this study that was similar to the correlation found by [22]. The results of this study were also confronted to the flexural strength than that exists in the ACI standard (ACI 318-08), namely MR = $\lambda * 0.62 * (f'_c)^{0.5}$ where λ is equal to 1.0 for normal concrete, 0.85 for sand-lightweight concrete, and 0.75 for all-lightweight concrete. Comparison of the graph shows that the flexural strength of porous concrete in the research is considerably higher than that of ACI standard. This indicates that volcanic pumice porous concrete has a good tensile strength and a capability to prevent the fracture due to impact loading. Volcanic pumice porous concrete can be developed to have a sufficient strength and good impact energy absorption as it has a low modulus of elasticity and a high tensile strength that provides a good impact energy absorption.

4. Conclusion

In the present paper, the effects of utilizing volcanic pumice as aggregate replacement materials for enhancing the mechanical properties (e.g. compressive strength and flexural strength) and quality control properties (e.g density and void content) of porous concrete is evaluated. The relationship between these properties are explored and compared to other researchers' works and ACI standard. Here we conclude that utilizing volcanic pumice on porous concrete mixtures resulting in a high porosity (void content) and a low modulus of elasticity of porous concrete. Moreover, by using volcanic pumice a higher tensile strength (flexural strength) than that of ACI standard can be obtained. This volcanic pumice porous concrete is potential for future structure with adequate strength and good impact energy absorbing. In addition, for estimating the modulus of elasticity of porous concrete, ACI 318-08 developed equation ($E_c = 0.043*W^{1.5}*f'_c{}^{0.5}$) can be used to rapidly estimate the modulus of elasticity of porous concrete, where it is necessary, due to experimental difficulties to measure it.

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